Background Oriented Schlieren (BOS) of a Supersonic Aircraft in Flight

James T. Heineck, NASA Ames
Daniel W. Banks, NASA Armstrong
Edward T. Schairer, NASA Ames
Edward A. Haering, Jr., NASA Armstrong
Paul S. Bean, NASA Armstrong

AIAA Flight Test Conference
June 13-17, 2016
Washington, DC

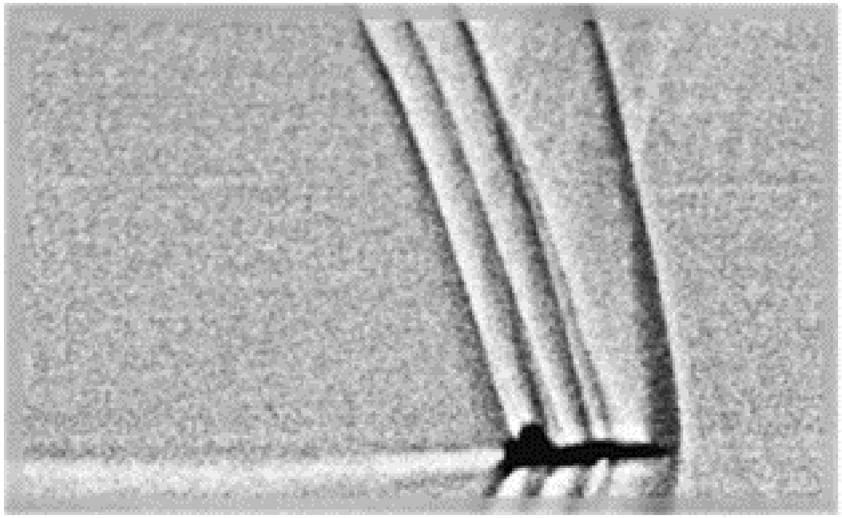
Introduction

- **Schlieren imaging for aerodynamics research was limited to ground test facilities**

- **Weinstein introduced the first reliable method for flight test in 1994**

- **Retroreflective Background Oriented Schlieren was demonstrated to work for full-scale aircraft in flight in 2012 (DLR Goettingen)**

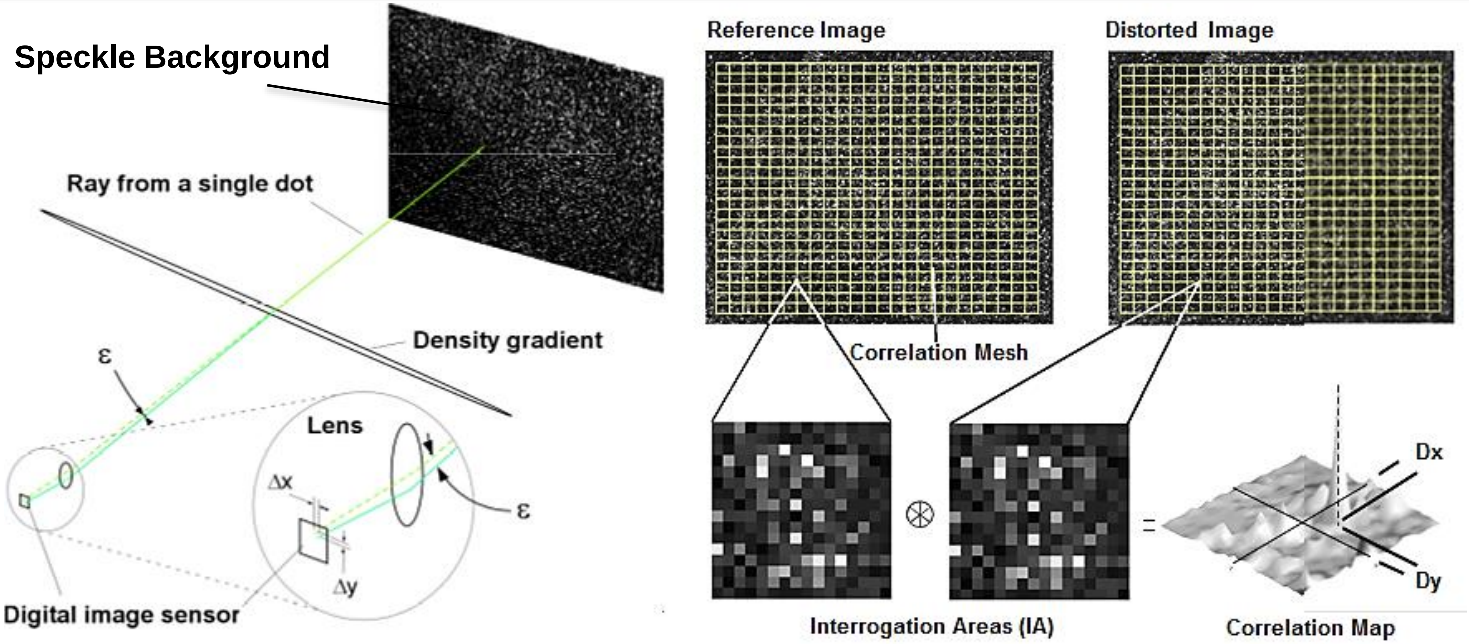
- **NASA's Commercial Supersonic Technology Program developed the next generation airborne schlieren methods for supersonic flight testing. First AirBOS flight in April, 2011 was successful, but restricted.**

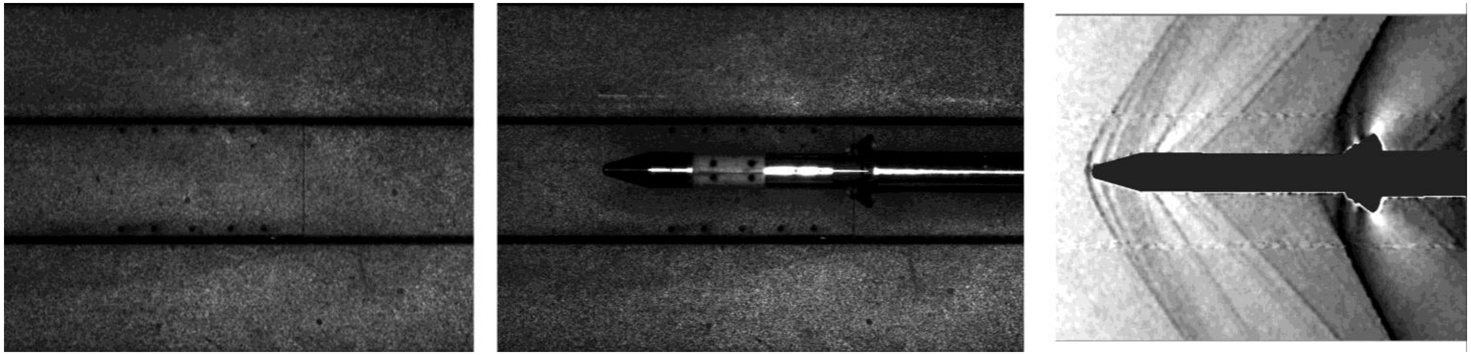


Weinstein's sun-edge streak camera image of a T-38

RBOS of a BO-105 in slow forward flight
Raffel, DLR Goettingen

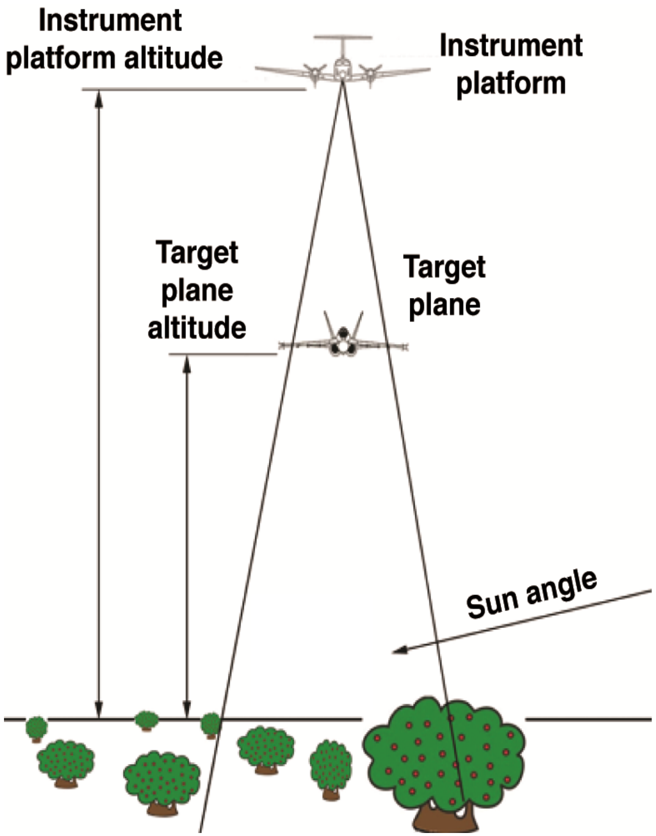
The BOS Method

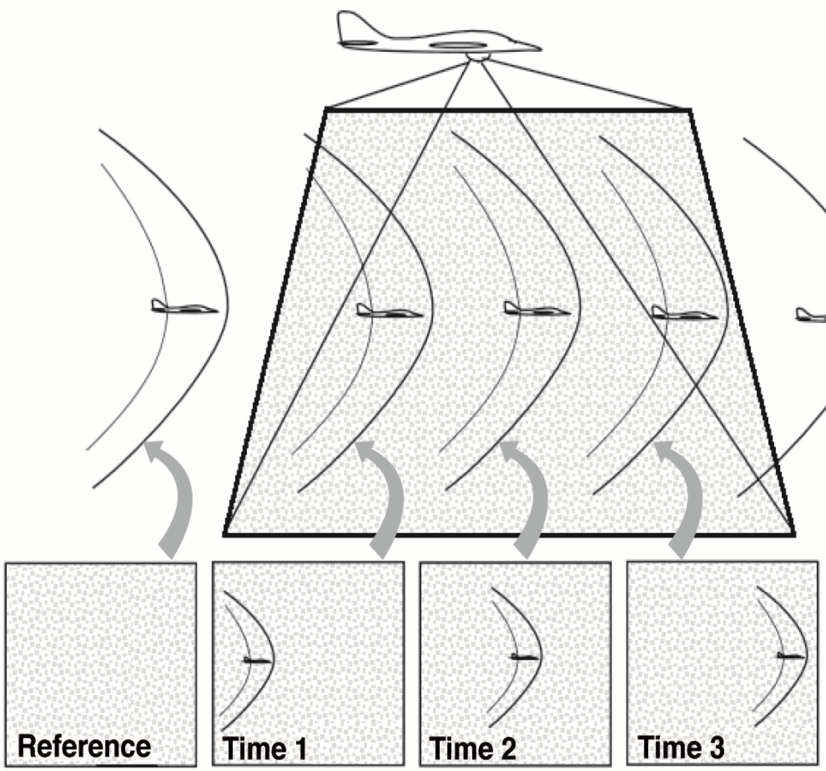




Wind tunnel reference, data image and result of an abort motor tower at M=1.3

The AirBOS Method





AirBOS Implementation

- Fly in the Supersonic Corridor near Edwards AFB
- Characterize the Mojave Desert flora in the Supersonic Corridor: Creosote bushes with scattered Joshua trees
- Bushes average 10 feet (3.1 m) diameter; too few trees to be of concern
- Dark green against light gray soil; red filter enhances contrast

Observer plane

NASA Beechcraft B-200 Super King Air

- ***Fly at 30,000 ft MSL (Highest practical altitude)***
- ***Low stall speed – 90 knots (75 knots at full-flap)***
- ***Already equipped with high-quality nadir port window***
- ***GPS navigation***

Target plane

Air Force T-38, operated by the Test Pilot School at Edwards AFB

Supersonic flight achieved by full acceleration during a shallow dive, leveling for the flyby

Imaging system design

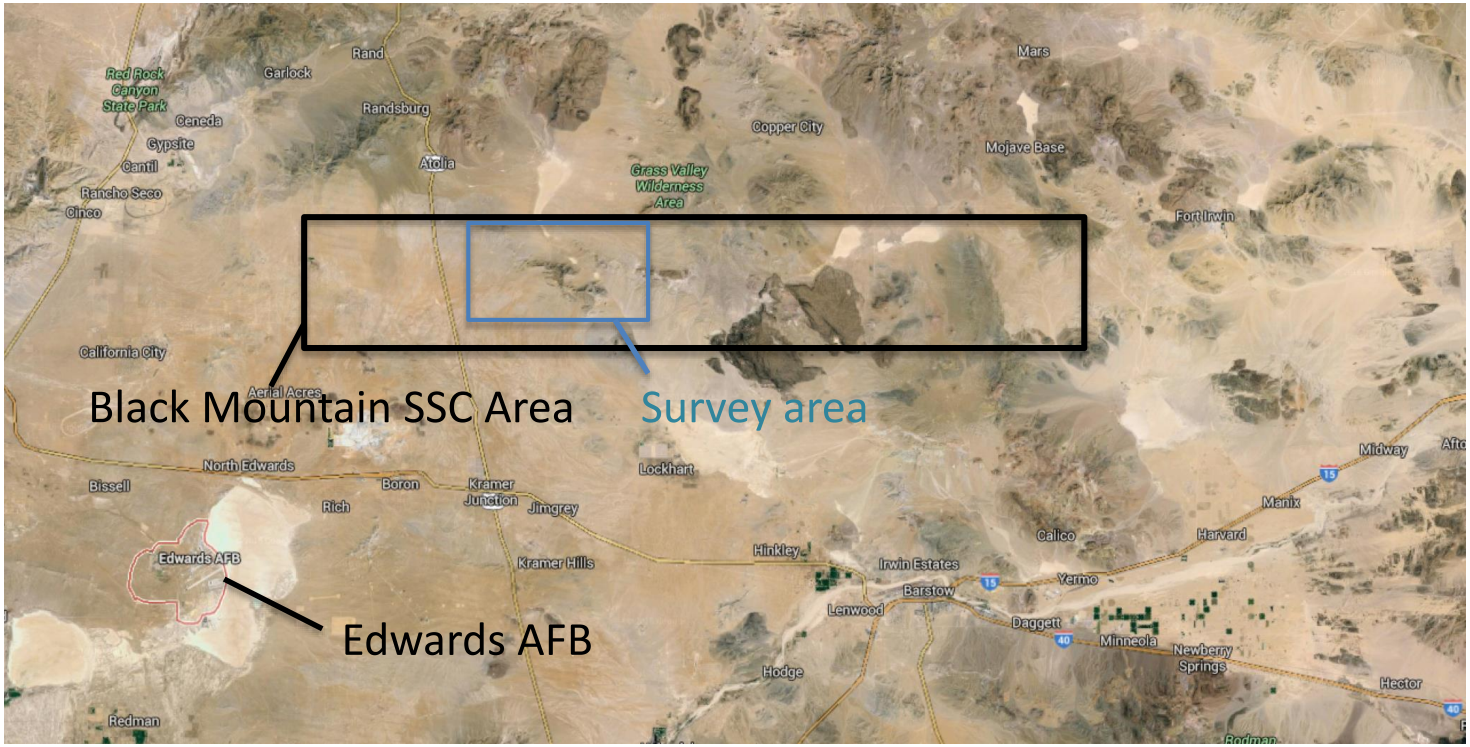
- Calculate the proper lens focal length to optimize speckle size
  - Phantom V641, with 2650 x 1600 pixel and 10 – micron pitch
  - Speckle distribution should be 2-5 pixels
  - Spreadsheet calculates pixel resolution and field of view on ground and at target location

Lens	Camera			Half Angles		Altitudes			FOV at Target Aircraft			FOV at Ground		
Lens fl (mm)	ccd nx (pixels)	ccd ny (pixels)	pixel size (µm)	X (Deg)	Y (Deg)	Observer a/c (Ft)	Target a/c (Ft)	Ratio	Δxfov (Ft)	Δyfov (Ft)	Resolution (pixels/ft)	Δxfov (Ft)	Δyfov (Ft)	Resolution (pixel / ft)
105	640	512	25	4.36	3.49	27000	13500	0.5	2057.14	1645.71	0.31	4114.29	3291.43	0.16
180	2560	1600	10	4.07	2.54	30000	26000	0.75	568.89	355.56	4.50	4266.67	2666.67	0.60
180	2560	1600	10	4.07	2.54	30000	28000	0.9	284.44	177.78	9.00	4266.67	2666.67	0.60

Sample of table for two cameras and target aircraft separation distances

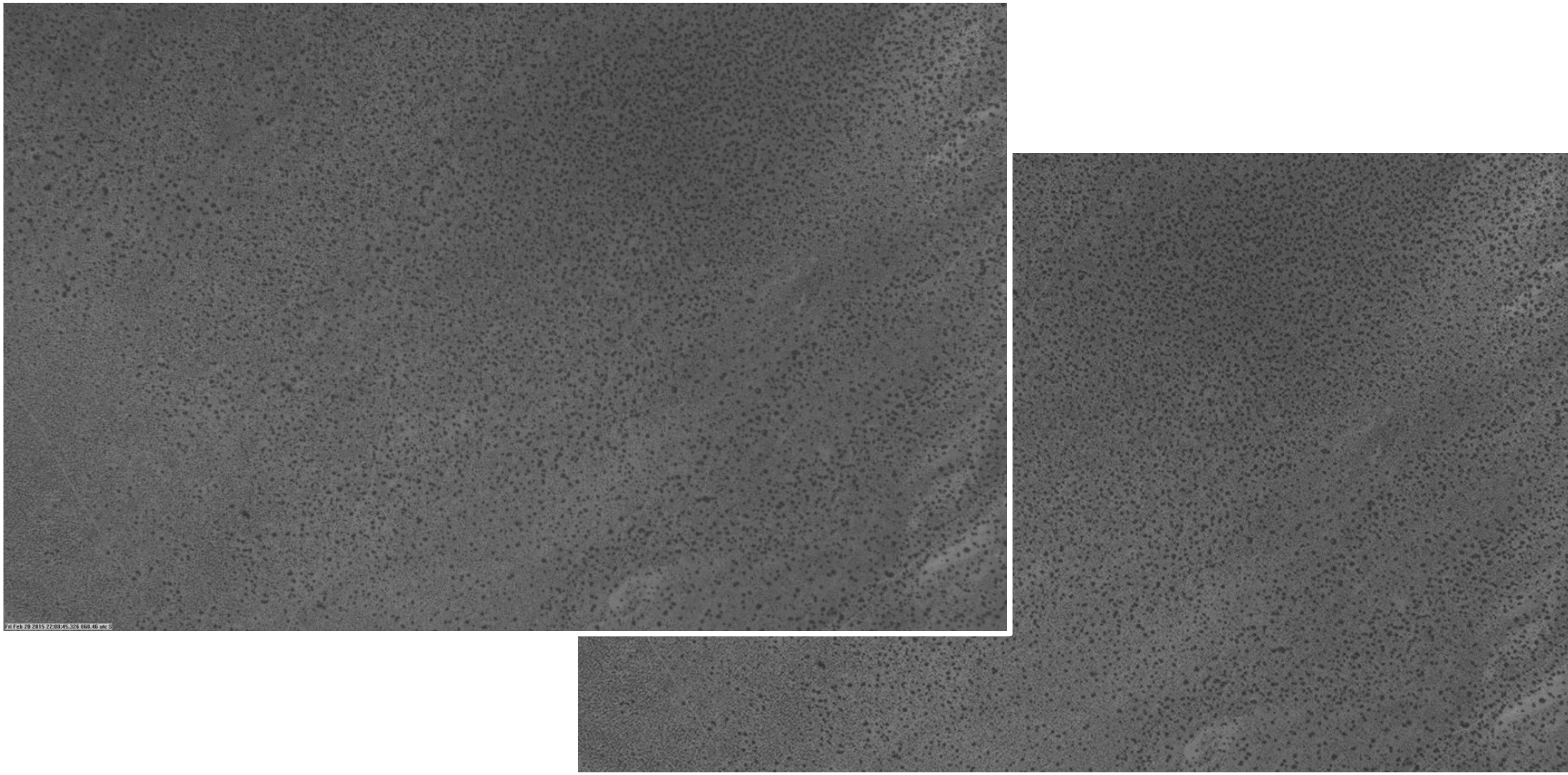
AirBOS Implementation

- **Survey the Black Mountain SS Flight Corridor at 30,000 ft altitude**
  - **Photographically survey large area, find consistent flora**
  - **Test for cross correlation performance**
  - **Design flight pattern to hit the "sweet spot" where the acceleration can be achieved, but turn around is within the corridor**



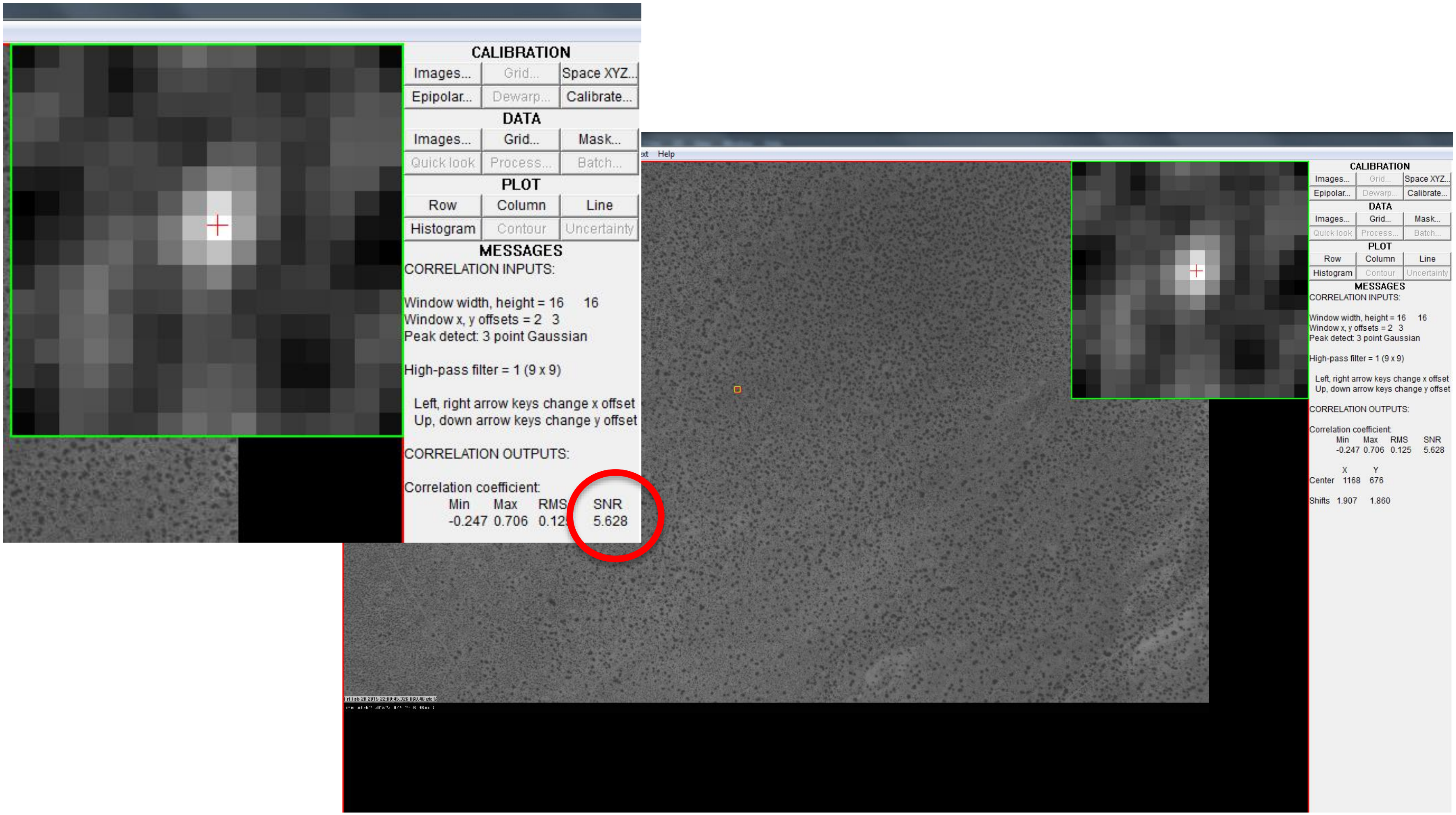
Google Earth view of area of Supersonic Corridor and Edwards AFB

Determining the Sweet-spot



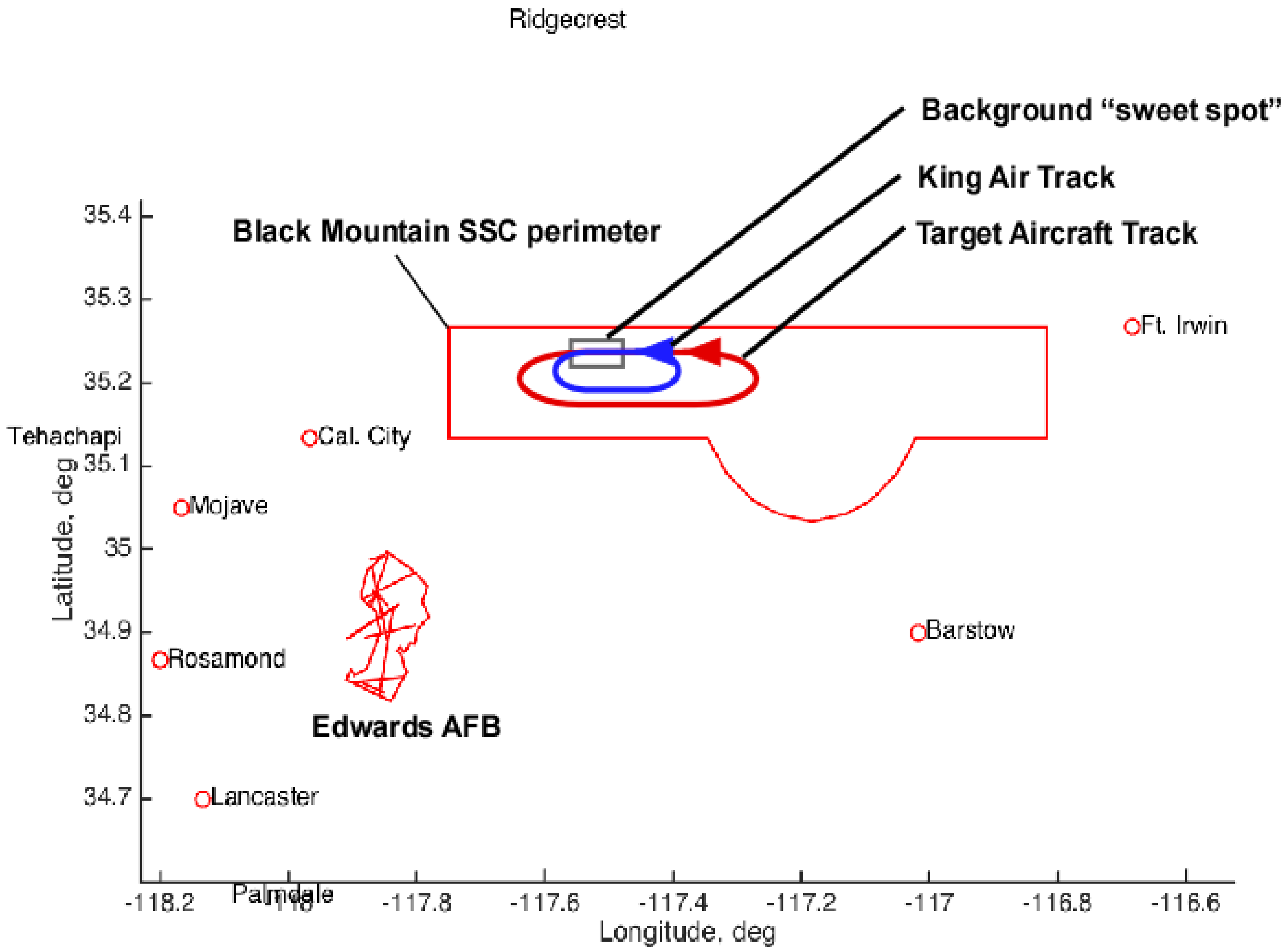
Evaluate two successive frames from the reconnaissance flight using cross correlation

Determining the Sweet-spot



Assure SNR of 5 or higher in the cross-correlation product using the anticipated window size

Flight Plan



Ridgecrest
Background "sweet spot"
King Air Track
Target Aircraft Track
Black Mountain SSC perimeter
Ft. Irwin
Tehachapi
Cal. City
Mojave
Barstow
Rosamond
Edwards AFB
Lancaster
Palmdale
35.4
35.3
35.2
35.1
35
34.9
34.8
34.7
Latitude, deg
-118.2
-118
-117.8
-117.6
-117.4
-117.2
-117
-116.8
-116.6
Longitude, deg

Cameras and Layout

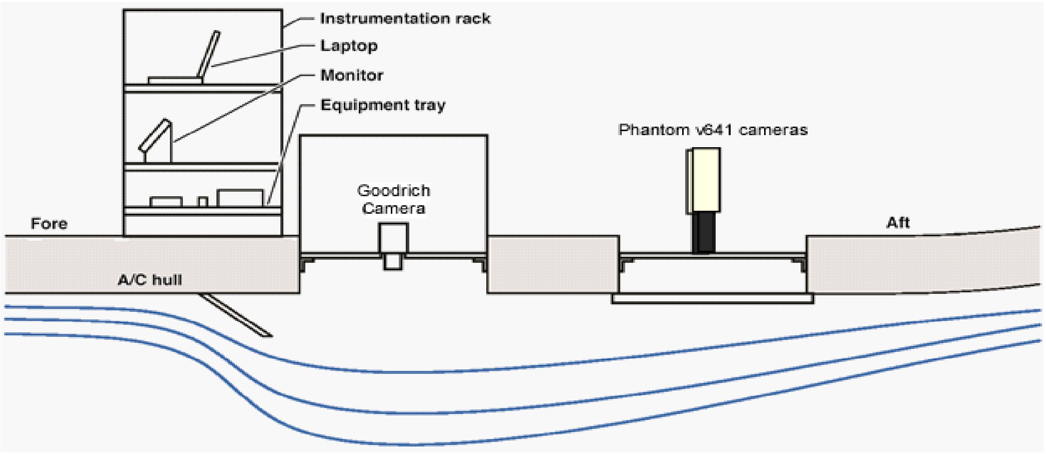
Phantom V641 monochrome, 2560 x 1600 pixels, 10 micron pitch, 180 mm lens

- 8 GB of internal memory, ~ 2 seconds of record time @ 1000 fps
- #25 Red filter, enhance contrast of bushes against the bright soil

Two cameras: redundancy and potential for stereo and multi-stream referencing

Legacy camera for 2011 work: Goodrich SUI SU640-SDWHVis-1.7RT InGaS

- 640 x 512 pixel sensor, 25 micrometer pixel pitch, and fitted with a 105 mm lens
- Used mainly as real-time spotting camera



Schematic of cabin layout

Two cameras, mounted vertically

Data Processing

1. Reference-to-data registration: First-order projective transform

- *Aligns the displaced backgrounds caused moving observer*

- *Corrects perspective distortion caused by pitch and roll during acquisition*

$$x = \frac{a_1x' + a_2y' + a_3}{c_1x' + c_2y' + 1}$$

$$y = \frac{b_1x' + b_2y' + b_3}{c_1x' + c_{2y'}{}_{+\,1}}$$

- *Four points at corner of images are chosen, large-window CC performed*

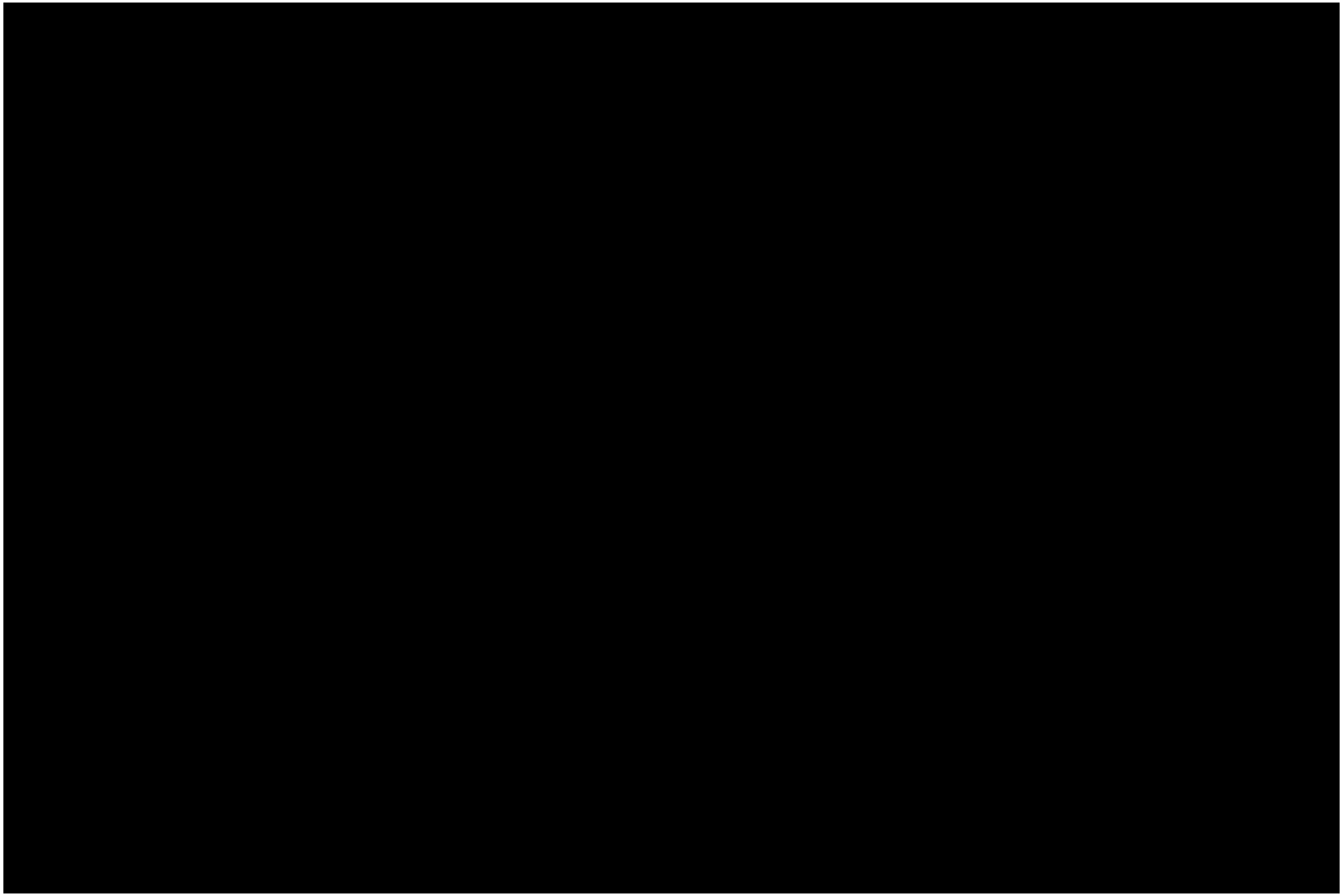
- *Cross correlation between the two images yields* Δx ***and*** Δy ***at each location,*** x' ***and*** y' ***are solved to then calculate the eight coefficients***

$$x' = x + \Delta x$$

$$y' = y + \Delta y$$

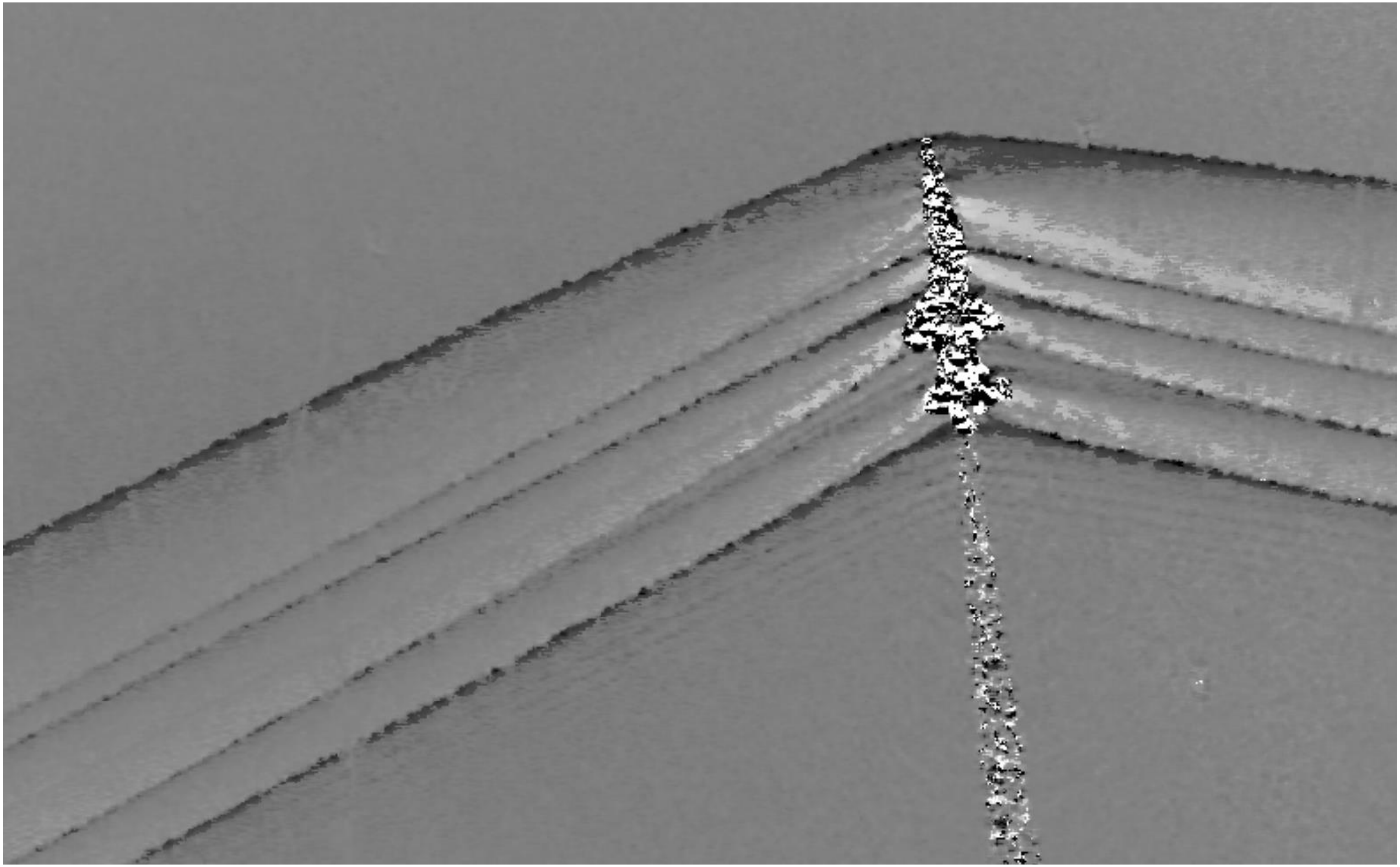
2. Image cross correlation at defined grid nodes yields Dx and Dy due to density gradient shift

AirBOS Results



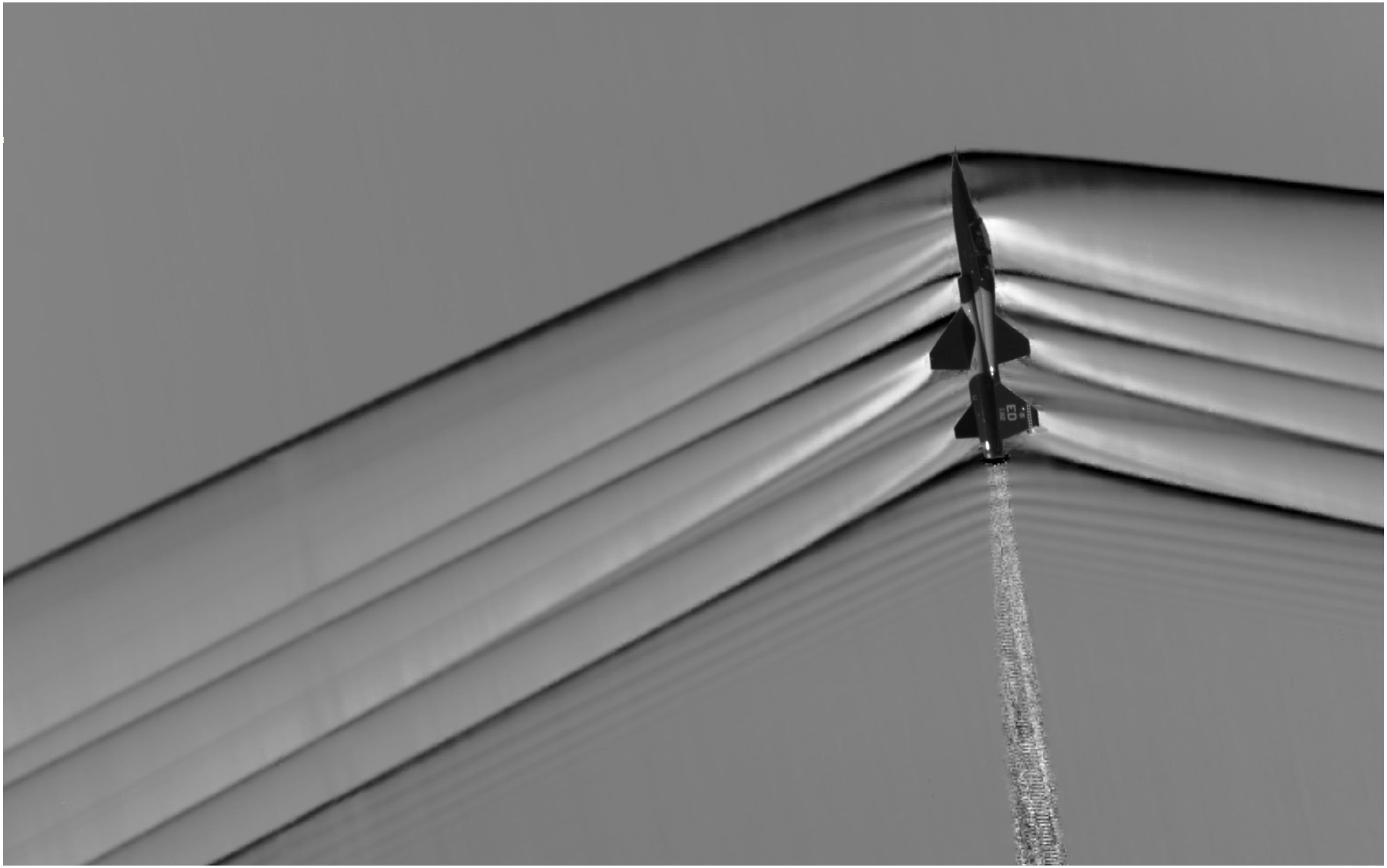
Sample movie of raw imagery, two frames skipped for brevity

AirBOS Results



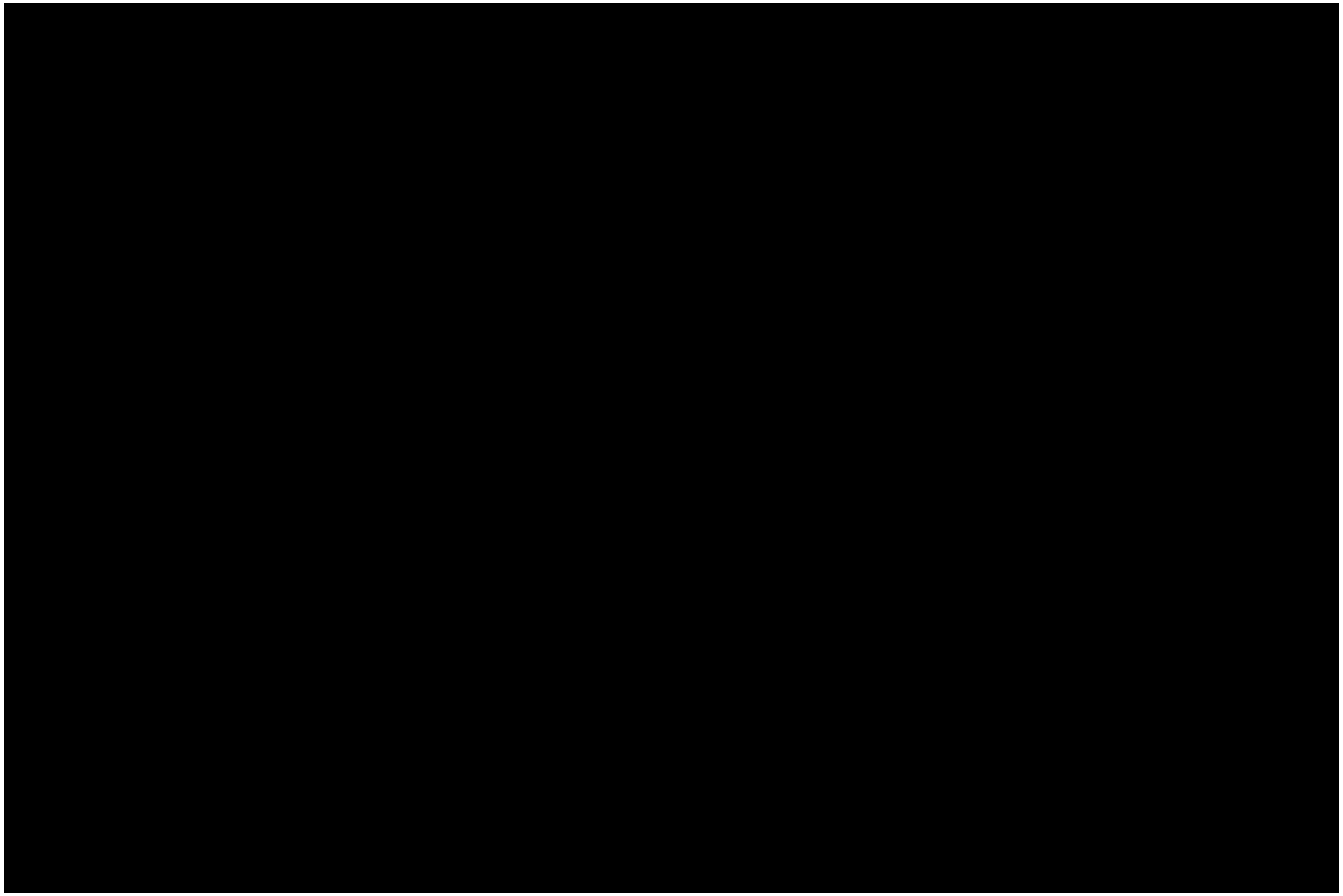
T-38 at 45 deg. roll, M=1.05, single frame, cross correlated to reference image

AirBOS Results



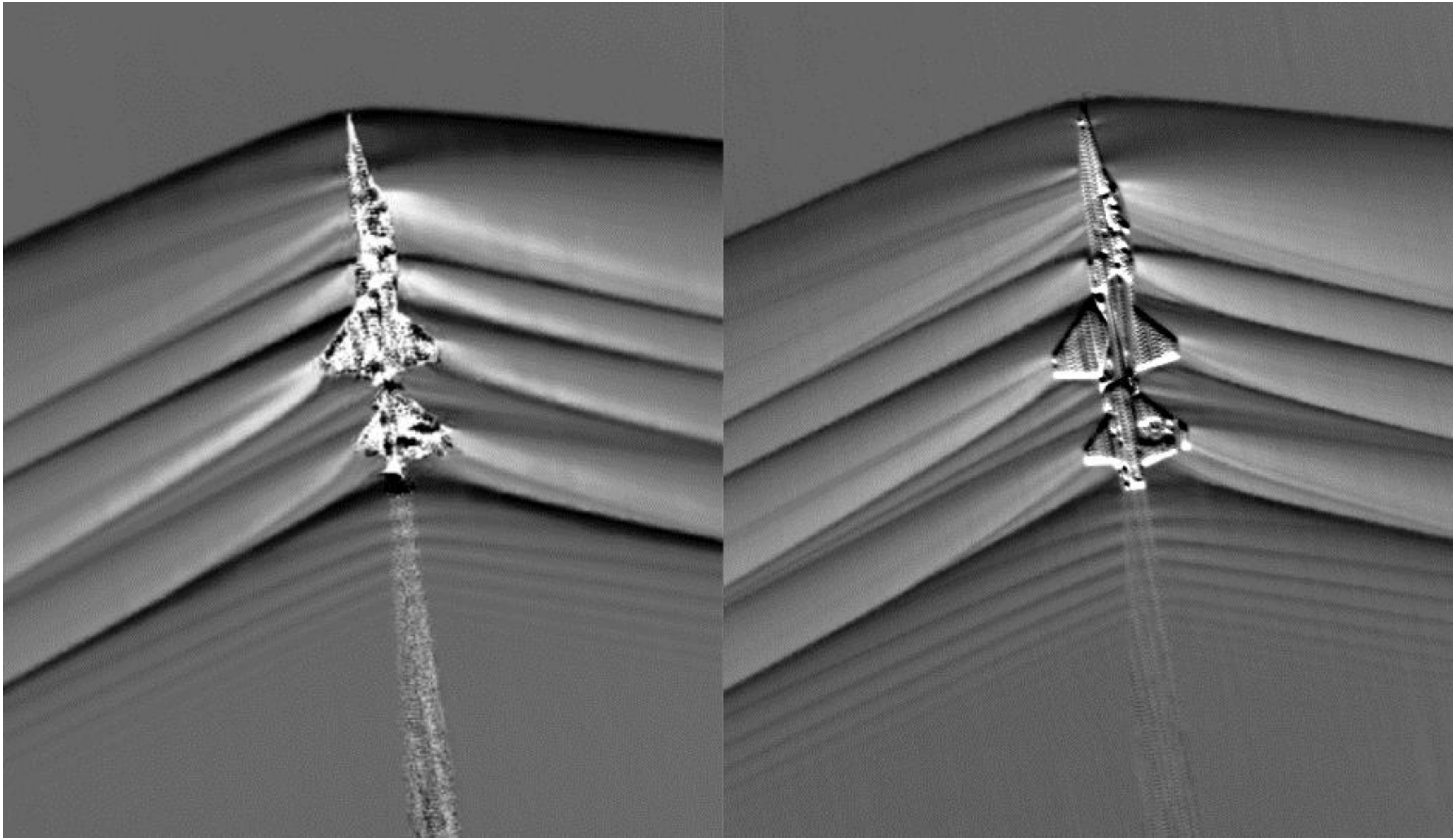
Results from 200 sequences aligned and averaged

Optical Flow: A new refinement



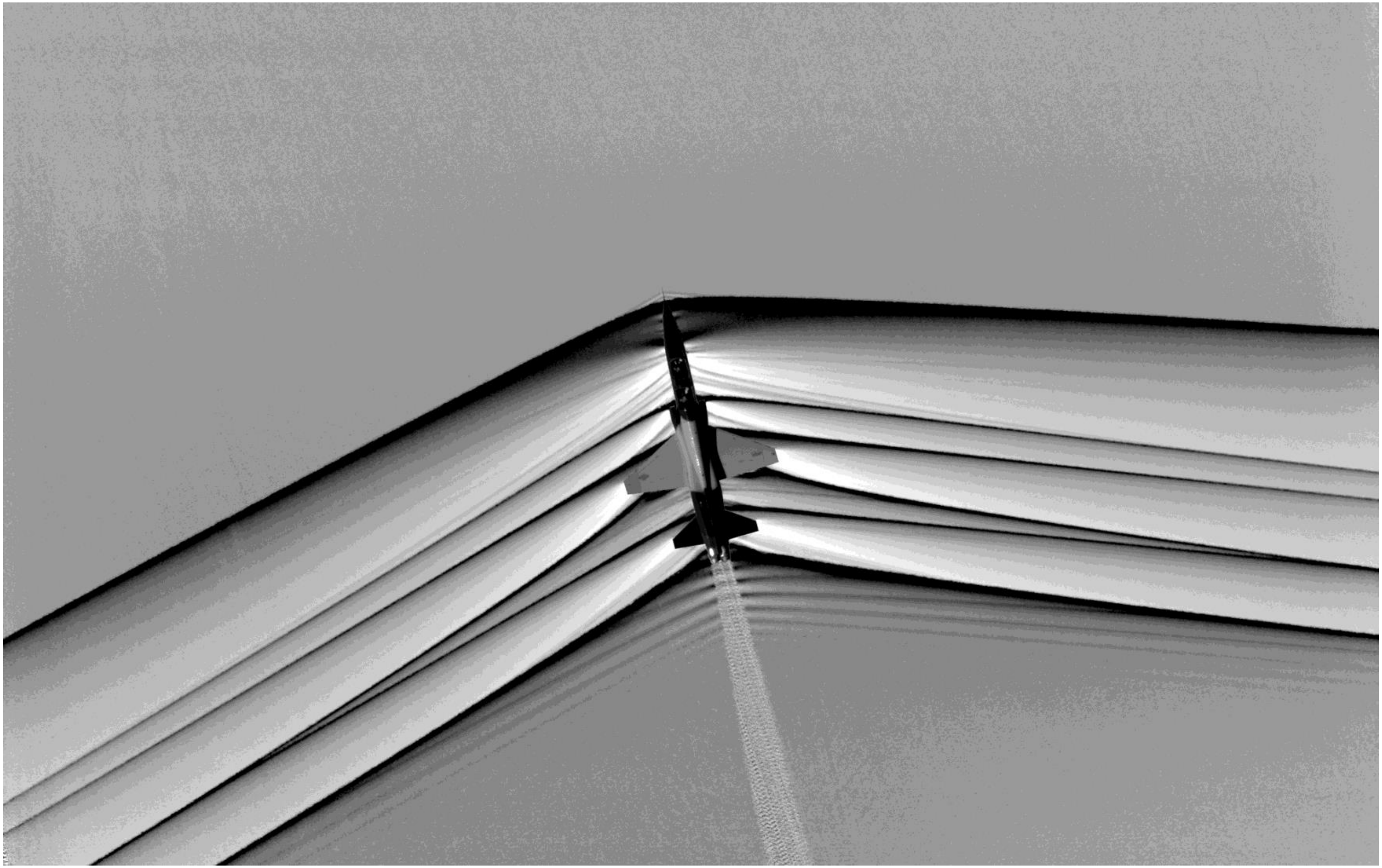
Movie of Optical flow-processed sequence, two frames skipped for brevity

AirBOS Results



Cross correlation average ***vs.*** ***Optical flow average***

AirBOS Results



T-38 at Mach=1.05, wings-level optical flow with 100 sequences aligned and averaged

Summary

Background Oriented Schlieren has been successfully adapted to full-scale supersonic flight

The planning and system design permit predictable results

Image processing has made the data of high quality – better than wind tunnel data

Technique permits testing of maneuvers, monitoring tip vortex trajectories, and subsonic wakes

Acknowledgements

Nils Larson, NASA Armstrong Chief Pilot and the flight crews

Maj. Jonathan Orso and Maj. Jeremy Vanderhal, Instructor Pilots from Air Force Test Pilot School

Brett Pauer, for flight test management

Peter Coen for years of support for this research

Neal Smith and Mike Hill for development of the Optical Flow algorithms